Alternative to Ni-Bearing Carburizing Steels

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Standard carburizing steel 18CrNiMo7-6 is often used when high hardenability is required, but due to its highly fluctuating price, there has always been an incentive to develop Ni-free steel grades. The 23MnCrMo5-5-2 — or Jomasco 23mod — has been developed for this purpose. But to ensure smooth substitution within existing production lines, a number of points must be addressed: first, checking the response to carburizing treatments; and second, having similar mechanical properties with identical tooth root bending performance on gears. The latter is the purpose of this paper.

Introduction

The mechanical industry uses large carburized parts, made out of the 18CrNiMo7-6 steel grade. Their carburizing depth can reach several millimeters and requires long heat treatment before the finishing operations of the hard surface. The deformations that can occur during this process should be minimized to ensure the best use. The choice between several steel alloys dedicated to these uses is also oriented by the carburizing response, especially concerning the stability of austenite grain size and the resistance to intergranular oxidation. The length of this manufacturing process raises interests in cost reduction sources.

In the automotive industry the 18CrNiMo7-6 is used to make some gearbox parts for commercial vehicles and also differential gear parts. This area is well known as being a leader in cost saving.

The replacement of this Ni steel must meet the two following requirements: 1) the new alloy must exhibit similar response to the carburizing treatment and 2) also to similar mechanical properties.

The 23MnCrMo5-5-2 has been developed (Ref. 1) in this context. The comparison with the 18CrNiMo7-6 (named as reference grade in the following) in terms of carburizing depth, retained austenite content, austenite grain stability and intergranular oxidation depth and mechanical properties has been previously published (Ref. 2). The chemical composition of both grades is illustrated in Table 1. The authors have demonstrated in (Ref. 2) that the 23MnCrMo5-5-2 can replace the reference grade without any modification of the carburizing process for moderate conventional carburizing depths (lower than 2.5 mm).

The results suggest that to reach high conventional carburizing depth, the carburizing time could in some cases be reduced by 10%.

This work focuses on the FZG tests that were performed to assess the comparison between the reference grade and the 23MnCrMo5-5-2 on carburized gears.

Gear Manufacturing

Gear geometry. Two gear geometries were used; their characteristics are shown in Table 2. Three separate sets of gears were made. Their manufacture consisted of hobbing, carburizing and hardening with carburizing processes. The first set of gears (with module 5, Gear 1), was tested as carburized. Surface strengthening was performed after the carburizing treatment for two sets of gears with module 10 (geometry Gear 2). A series has been mechanically cleaned; the other has been submitted to shot peening.

Since the actual tooth root geometry has a strong influence on the load/tooth-root- stress conversion factors, one tooth with two neighbor flanks of each test series was scanned, and the effective geometrical data of the analyzed gears were determined. Figure 1 shows the scan of the actual gear geometry of the module 5 gears with the corresponding geometrical data. Figure 2 shows the scan of both the module 10 gears series as well as the theoretical geometry. It can be observed that, due to the grinding process, an undercut can be seen near the 30° tangent of the tooth root fillet of both shot peened gears. This undercut will certainly increase the tooth root stress. In interaction with the residual stresses due to the performed shot peening after the grinding process, the negative effect of the undercut should be reduced. The interaction of both effects (undercut and shot peening) cannot be

Table 1 Chemical composition in wt% of reference 18CrNiMo7-6 and designed 23MnCrMo5-5-2 grade, as obtained using optical emission spectrometry and LECO analysis for carbon content (*)

Steel grade	C*	Si	Mn	Ni	Cr	Mo
18CrNiMo7-6	0.18	0.21	0.52	1.55	1.67	0.30
23MnCrMo5-5-2	0.21	0.26	1.35	0.24	1.28	0.23

Table 2 Gear data for bending tests

Parameter	Symbol	Gear 1	Gear 2	Unit
Normal module	mn	5	10	mm
Number of teeth	z	24	24	-
Pressure angle	α	20	20	°
Helix angle	β	0	0	°
Face width	b	30	30	mm
Add. Mod. Factor	x	2.43	4.15	mm
Tip diameter	d_a	134	268	mm

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calculated exactly according to the current state of the art. An estimation of the influence of the undercut is proposed later on. For both grades the measured geometry as well as the undercut is comparable.

Residual stress evaluation. X-ray diffraction allows the assessment of the difference between the three series of gears. X-rays are produced by a tube with a chromium anode; displacement of the alpha {211} peak is studied.

After 25 μm etching the residual stresses were evaluated for one gear of each type; the uncertainty is evaluated to ± 40 MPa. Both grades have similar levels of residual stresses; results are shown in Table 3. As carburized, the surface exhibits compressive residual stresses of roughly 200 MPa. After the mechanical cleaning process, the level of compressive residual stresses has been doubled compared with the as-carburized state and multiplied by a factor 4 to reach –850 MPa on the shot peened gears.

Metallurgical characterization. All fatigue tests were done by FZG in Munich. Both hardness measurements and microstructure investigations were performed after the tooth bending tests on a tooth failed by tooth root breakage. Figure 3 locates the measurement of the carburizing depth in the tooth root fillet.

Retained austenite content has been evaluated in CREAS (Colloquium on the Resolution of Equations in Algebraic Structures) using X-ray diffraction on a cut tooth. Therefore a diffractometer with a chromium anode tube was used. The intensity of the three gamma peaks — 111, 200 and 220 — and the alpha peaks 110 and 200 — were used.

In Tables 4–6 the main results of the metallurgical features are summarized and shown for both grades, respectively — i.e., for the non-peened module 5 gears, the mechanically cleaned module10 gears, and the shot peened module 10 gears.

According to (Ref. 4), the recommended carburizing depth (550HV, or referred to hereafter as "Eht") in order to avoid tooth root bending rupture should be in the range 0.1* mn and 0.2* mn.

For the non-peened gears, both microstructure and hardness profiles correspond to the state-of-the-art of case carburized gears; only small differences were found. Those were a slightly higher Eht and higher core hardness for the 23MnCrMo5-5-2 in comparison to the reference grade; also, the Eht of the 23MnCrMo5-5-2 slightly exceeded the recommended range (0.24*mn).

The mechanically cleaned gears are similar in terms of metallurgical features. Furthermore, the Eht respects the recommendations of (Ref. 4) with 0.13* mn.

Due to the undercut in the tooth root fillet of the shot peened gears, the Eht is lowered in comparison to the Eht after heat treatment. However, all Eht are within the limits, according to the recommendation of (Ref. 4), 0.13* mn.

Test Method

The gear teeth were clamped symmetrically and tested over four teeth between two jaws. The type of device used for the three gearsets is shown (Fig. 4). The load direction was tangential to the base circle. Flank angle deviations were compensated by means of a precision adjustment so that a uniform load distribution across the whole face width could be assumed. The test gear was friction-locked between both jaws, therefore a preload was needed. This preload is indicated in Table 7 for the three test rigs used.

The pulsating load was calculated as the difference between the maximum load and the minimum lorad ($F_{Pn} = \Delta F = F_{P\,max} - F_{Pmin}$). The ratio R between the maximum and the minimum

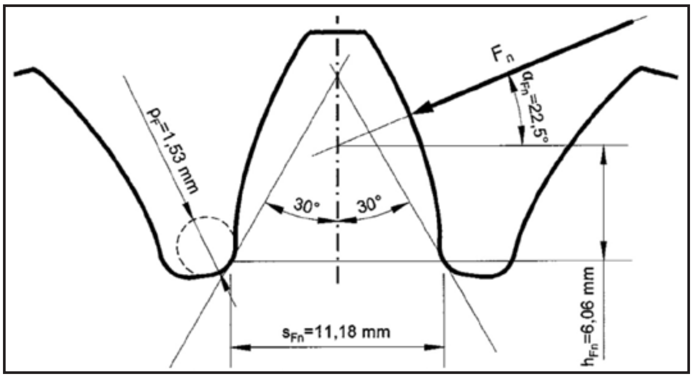

Figure 1 Evaluation of actual geometry and of the main geometrical data of module 5 gears.

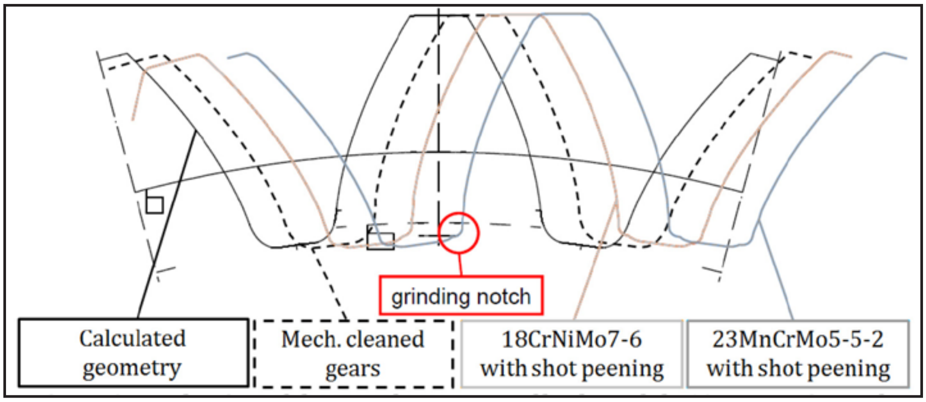

Figure 2 Evaluation of actual geometry of both module 10 gear series and comparison with calculated geometry.

Table 3 Residual stresses evaluated using X-ray diffraction after 25 µm etching

Steel grade	Unpeened	Mechanically cleaned	Shot-peened
18CrNiMo7-6	- 200 MPa	- 380 MPa	- 868 MPa
23MnCrMo5-5-2	- 162 MPa	- 456 MPa	- 834 MPa

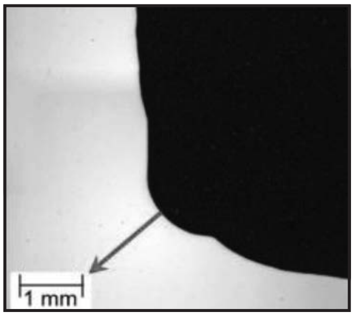

Figure 3 Schematic direction of measurement of CHD in tooth root fillet.

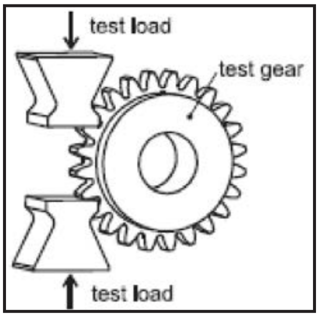

Figure 4 Clamping of test gear for bending test.

Table 4 Metallurgical features of non-peened gears

Grade		18CrNiMo7-6	23MnCrMo5-5-2
Surface Hardness (HV1)	Flank	698	704
	Tooth root fillet	736	728
Eht 550 (mm)	Flank	1.13	1.28
	Tooth root fillet	0.96	1.22
Core hardness (HV1)		449	474
Intergranular oxidation (p.m)		10–12	12–14
Surface microstructure		Martensite and retained austenite	
Core microstructure		Martensite and bainite	
Retained austenite (%)		31	37

Table 5 Metallurgical features of mechanically cleaned gears

Grade		18CrNiMo7-6	23MnCrMo5-5-2
Surface Hardness (HV1)	Flank	663	664
	Tooth root fillet	669	677
Eht 550 (mm)	Flank	1.25	1.36
	Tooth root fillet	1.33	1.35
Core hardness (HV1)		419	404
Intergranular oxidation (m)		12–14	7–12
Surface microstructure		Martensite and retained austenite	
Core microstructure		Martensite and bainite	

Table 6 Metallurgical features of shot peened gears

Grade		18CrNiMo7-6	23MnCrMo5-5-2
Surface Hardness (HV1)	Flank	712	720
	Tooth root fillet	768	656
Eht 550 (mm)	Flank	1.78	1.76
	Tooth root fillet	1.49	1.37
Core hardness (HV1)		404	380
Intergranular oxidation (p.m)		15–19	17–32
Surface microstructure		Martensite and retained austenite	
Core microstructure		Martensite and bainite	Bainite
Retained austenite (%)		27	21

Table 7 Test conditions according to each device

Type of gear	Unpeened	Mechanical cleaned shot peened	shot peened
Type of pulsating rig	Hydraulic	Electro-magnetic	Mechanical
Underload	4 kN	7.5 to 10 kN	10 kN
Load step	1.5 to 3 kN	5 to 10 kN	10 kN
Tested teeth	12	5 to 7	7
Frequency	40 Hz	115 Hz	35 Hz

load ($R = F_{P/min}/F_{Pmax}$) was 0.1. The pulsating load characteristic was sinusoidal; each frequency used with each test rig is given in Table 7. An influence of the frequency on the test results has not been detected.

The endurance level was determined following the "staircase method," with 5 to 12 data-points-per-batch. The fatigue limit is assumed to be the fatigue strength at 6.106 cycles for 50% failure probability.

The endurance strength in bending is calculated according to the method explained in (Ref. 4).

Test Results and Discussion

Gears, as carburized, and gears carburized and mechanically cleaned. Figures 5 and 6 show the nominal bending stress number that was determined for both materials on the basis of the nominal tooth root bending stress for endurance limit with a 50% failure probability for two states — as-carburized and carburized — and mechanically cleaned. On the basis of this parameter gears can be allocated in a defined quality range called ML, MQ and ME, and shown on both charts.

The 18CrNiMo7-6 gears and the 23MnCrMo5-5-2 tested in the as-carburized state show similar nominal bending stress numbers. The ML quality range is reached. When they are compared to previous data obtained by FZG, both grades show slightly better performances. These results are in good agreement with (Ref. 4). The following indication is given: "Values of MQ bending stress were achieved with adequate industrial cleaning techniques applied and therefore cannot necessarily be achieved after heat treatment alone." The results obtained for the gears that have been carburized and mechanically cleaned illustrate this citation nicely. Both the reference and the 23MnCrMo5-5-2 reach the MQ quality level. Once again, both grade performances are similar.

Test results on shot peened gears. For the carburized shot peened gears the tooth root stress is calculated first without considering the stress increase due to the undercut. The nominal bending stress number obtained for the 18CrNiMo7-6 is 474 N/mm², whereas it is evaluated to 485 N/mm² for the 23MnCrMo5-5-2. As the defect in the tooth root fillet was similar for both grades, the results can be directly compared. Once again, the gears made out of the 23MnCrMo5-5-2 have similar performances to the gears made out of the 18CrNiMo7-6.

The undercut certainly increases the real tooth root stress introduced during testing. Estimating the decreasing effect of the undercut according to (Ref. 5), the negative effect should be within a range of 10 to 20% in comparison with a non-grinded shot peened tooth root fillet. Using a finite element simulation (*Forge 2011* software), we have tried to evaluate this difference more precisely.

The Von Mises equivalent stress was evaluated using a 2-D model of the perfect theoretical gear geometry (elastic behavior). The mesh was refined in the tooth root region; the same calculation was done using the geometry with the undercut. The Von Mises equivalent stresses obtained for each geometry are compared according to the crack direction observed on gears after fatigue tests. It is illustrated in Figure 7 in grey for the standard geometry, and in white for the tooth root, including the defect. The evolution of the Von Mises equivalent stresses in both cases was plotted (Fig. 8). We con-

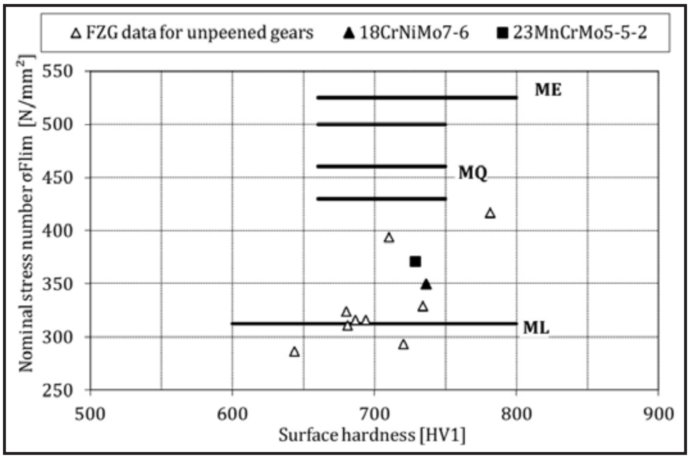

Figure 5 Comparison of nominal stress number obtained on un-peened gears made of 18CrNiMo7-6 and 23MncrMo5-5-2 with FZG data on similar samples and ISO6336-5 quality levels.

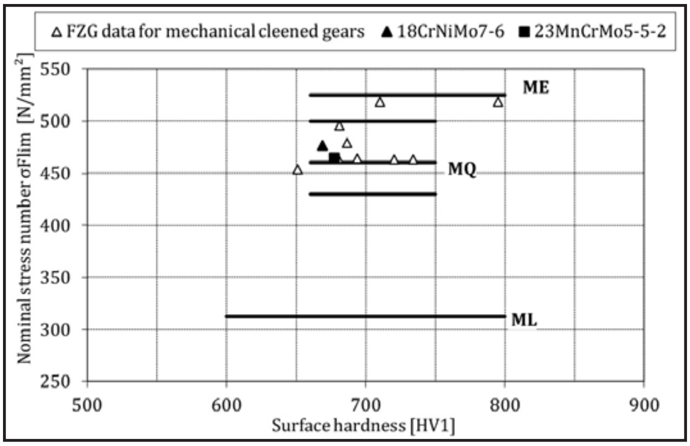

Figure 6 Comparison of nominal stress number obtained on mechanically cleaned gears made of 18CrNiMo7-6 and 23MnCrMo5-5-2 with FZG data on similar samples and ISO6336-5 quality levels.

sidered that the correct stress evolution begins above 250 μm from the surface. Using polynomial fit of these curves, the equivalent stress at the surface has been evaluated. An equivalent stress of 645 Mpa is estimated for the standard geometry. The undercut leads to an increase to 749 MPa. Supposing that the ratio of these equivalent stresses is identical to the ratio of the bending stresses, the undercut stresses are 16% greater than the standard geometry.

Figure 9 shows (white symbols) the results calculated by FZG without considering the geometry defect. A rise of 10% is shown by the lowest black symbols, a rise of 16% leads to the highest black symbols showing that the ME quality level could be reached by a carburized, shot peened gear made out of either 18CrNiMo7-6 or 23MnCrMo5-5-2—with the correct geometry.

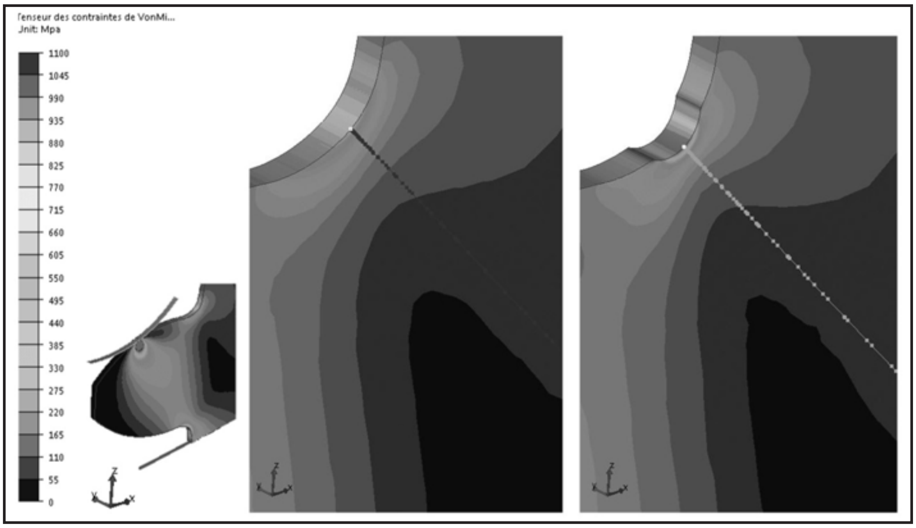

Figure 7 Von Mises stresses evaluated by FE method on gear with undercut (right image) and reference gear (left) submitted to same load.

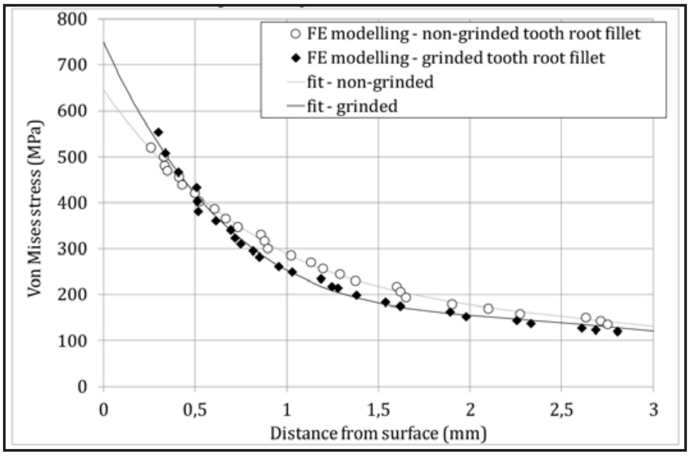

Figure 8 Evolution of Von Mises equivalent stress for standard geometry and grinded geometry.

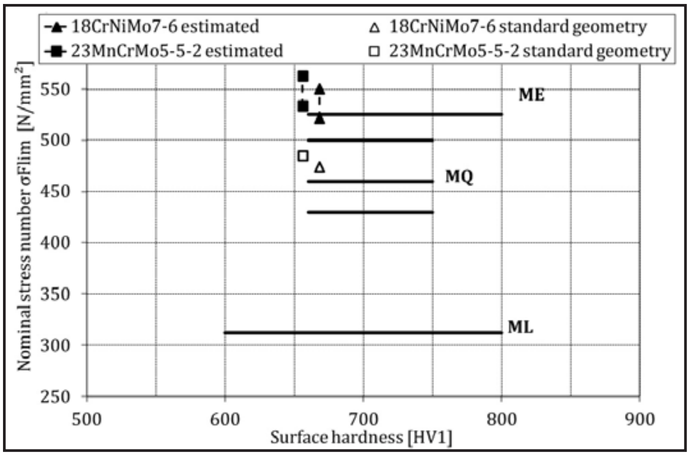

Figure 9 Comparison of nominal stress number obtained on shot peened gears made of 18CrNiMo7-6 and 23MncrMo5-5-2 with FZG data on similar samples and ISO6336-5 quality levels.

Conclusions

Thanks to an appropriate alloying choice, the 23MnCrMo5-5-2 is cheaper than the 18CrNiMo7-6.

The comparison with the 18CrNiMo7-6 (named as reference grade in the following) in terms of carburizing depth, retained austenite content, austenite grain stability and intergranular oxidation depth and mechanical properties has been previously published (Refs. 2–3). The Ni-free grade 23MnCrMo5-5-2 is virtually identical to the 18CrNiMo7-6 in terms of hardenability and mechanical properties in reference conditions. It was also shown that the reference grade can be replaced by the 23MncrMo5-5-2 without any adjustment to the carburizing parameters.

Three sets of gears were tested by FZG. Both grades were carburized in the same batch of heat treatment. X-ray diffraction measurements were performed to evaluate the residual stresses. The first set of gears was tested as-carburized. Both grades reached the ML quality level defined in (Ref. 4), with similar results. The second set experienced a mechanical cleaning after the carburizing treatment. These gears reached the MQ level of quality, once again with similar performances for both grades. Shot peening was performed on the third set, post-carburizing. Those gears achieved the ME level with similar results for the gears made out of 23MnCrMo5-5-2 and those made out of 18CrNiMo7-6. So, in addition to previously published work, the FZG test results that are detailed here demonstrate that the 23MnCrMo5-5-2 can replace the 18CrNiMo7-6 with no change in performance. **PTE**

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Upon graduation (M. Engineering) in 2005 from INSA Lyon, **Mathilde Millot-Meheux** subsequently was awarded her PhD from Ecole Centrale de Lyon and INSA Lyon in 2009 — based upon the study of the influence of lubricant additives on tribofilm formation, friction coefficient and rolling contact fatigue life of rolling bearings. In that same year she began work as a research engineer in the Service Properties and Machinability research group at the R&D center of the French steel manufacturer Asco Industries. In that role Millot-Meheux's primary responsibility is the development of rolling bearing steels and gear steels.

Thomas Sourmail in 2006 was named manager of the Metallurgy research group for the Asco Industries R&D Center, located in the east of France. From 2002–2005, he worked as a research assistant at Cambridge, focusing on precipitation modeling in various systems, e.g. — FeCo, and super-alloys; from 2005–2006 he served as Project Leader for a group devoted to work on primarily ferritic materials. In his current managerial role, Sourmail oversees new product development for the various markets in the Asco Industries portfolio, including steels for the automotive and off-road industries — forging steels, carburizing steels, bearing steels, etc. — and also for O&G-type applications. Sourmail has been published in more than 40 peer-reviewed publications and journals and is the holder of a number of active patents.